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A Labeled Lines Explanation of the Perceived Spatial Frequency of Moderate-, Near-threshold- and Zero-contrast Spatial Patterns

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We tested the predictions of a multiple-channels model about the appearance of spatial patterns. Specifically we tested how encoding the perceived spatial frequency of a near-threshold pattern compared with encoding of a zero-contrast or moderate-contrast pattern. For example, the model predicts that the mean perceived spatial frequency of a near-threshold pattern is a weighted average of the response to the stimulus and the noise. Six subjects used the method of adjustment procedure to match a peripherally viewed test stimulus (or a blank) with a foveally viewed grating. For near-threshold patterns we found a smooth perceived spatial-frequency function, with a smaller range of perceived spatial frequencies than obtained for 0.16 contrast patterns. These results are consistent with the predictions of the model: noise can affect the appearance of near-threshold and zero-contrast patterns.

Labeled lines   Perceived spatial frequency   Spatial-frequency channels   Noise   Signal detection theory

A few decades ago, Krauskopf and his colleagues (Krauskopf, 1964, 1978; Krauskopf & Srebro, 1965) demonstrated that one could stimulate a single color labeled line with the appropriate stimulus and adaptation conditions. They presented very small, brief, dim, monochromatic flashes to the fovea on most trials and a blank on 12.5% of the trials. The experimental conditions were chosen so that the subject did not always report seeing the flash stimuli but never reported flashes on any blank trials. That is, the flashed stimuli were near the detection threshold and no false alarms were reported. Following each flash, the observer set a second monochromatic, suprathreshold stimulus to match the perceived hue of the preceding flash.

Figure 1 shows a summary of some of their data. The top panel shows a frequency histogram of the monochromatic perceptual match settings to all of the pooled test wavelengths. The distribution of the match settings is bimodal, with peaks at about 500 and 625 nm. The lower panels show the distributions of the perceptual match settings for each of the individual test wavelengths. The individual histograms all have the same bimodality as the grouped data; the only difference is the relative heights of the 500 and 625 nm peaks. The interpretation was that, on a given trial, only one of two labeled lines was activated. Through further experimentation, they showed that the two labeled lines had spectral sensitivities similar to those of the middle- and long-wavelength sensitive cones, corresponding to perceived hues of "green" and "reddish-orange", respectively.

Several investigators (Hirsch, Hylton & Graham, 1982; Olzak & Thomas, 1981; Watson & Robson, 1981; Yager, Kramer, Shaw & Graham, 1984), using several different methods, have shown that labeled lines also may exist in human spatial vision. In many of these studies, observers not only reported whether they detected a stimulus, but they also reported which of two to four stimuli of very different spatial frequencies had been presented. If each of two spatial stimuli can be identified at the same contrast as it is first detected, the two stimuli must be detected by separate channels, each with a unique perceptual label. Experimental results indicate that there are multiple spatial-frequency channels operating at an early stage in human spatial vision. Furthermore, the outputs of these channels do have unique perceptual labels and, at near-threshold

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contrasts, these labels remain distinguishable further upstream in the visual system.

We extended our understanding of these labeled lines by examining how the spatial-frequency channels (or labeled lines) encode the appearance of near-threshold sinewave gratings, as compared with blank or supratheshold stimuli.* To do this, we tried to stimulate only a single channel. First, we used near-threshold test stimuli. Second, we tried to restrict the underlying channels to only a few discrete channels. That is we restricted the test spatial frequencies to the high spatial-frequency end of the range, where only two, or at most three, underlying spatial-frequency channels operate (Swanson & Wilson, 1985; Wilson, McFarlane & Phillips, 1983).† We also tested at 8 deg in the superior visual field because this region of the periphery is more spatially homogeneous than is the fovea (Graham, Robson & Nachmias, 1978; Richter & Yager, 1984; Swanson & Wilson, 1985). Thus, fewer spatial frequency channels would respond to a patch of vertical sinewave grating presented at 8 deg in the superior visual field than to a patch presented in the fovea.

THEORY

By stimulating only one or two of a restricted set of discrete channels, we can test the predictions of a multiple-channels model about the appearance of spatial patterns. By relating our data to the model predictions we may reveal how humans encode the perceived spatial frequency of a near-threshold spatial pattern, as compared with that of a zero-contrast or a moderate-contrast pattern. First, we will discuss the assumptions of a multiple spatial-frequency channels model. Second, we will present the model predictions. Later, in the Discussion Section, we will compare the predictions to our empirical results. In the Discussion we also will consider the predictions of a high-threshold model and why the high-threshold model probably cannot

*This research is based on earlier empirical studies (Yager, Davis, Lee & Neufeld, 1989) and preliminary computer simulations (Davis, Yager, Richter, Woodward & Kramer, 1984). This article is a more complete and fully developed version of this earlier research.

†Some evidence why these conditions should reveal the operation of only a few discrete channels is given here. At the high and low ends of the spatial frequency range, the threshold elevation curves obtained from masking data indicate only a few discrete channels are operating (Wilson *et al.*, 1983). That is, at either the high or low end of the spatial frequency range, the masking function will peak at the same spatial frequency regardless of the specific test spatial frequency used. This could only happen if there were discrete spatial frequency channels, rather than a continuum of channels. For intermediate spatial frequencies, however, the masking data are compatible with the operation of either a discrete set or a continuum of spatial-frequency channels. Moreover, for channels located at 8 deg in the superior visual field, both masking data and contrast matching data show that the underlying set of spatial-frequency channels has been scaled to lower spatial frequencies than the foveal set of channels (Swanson & Wilson, 1985). Hence, at 8 deg in the superior visual field, 4 c/deg would be a high spatial frequency that would be detected by one of the two highest spatial-frequency channels.

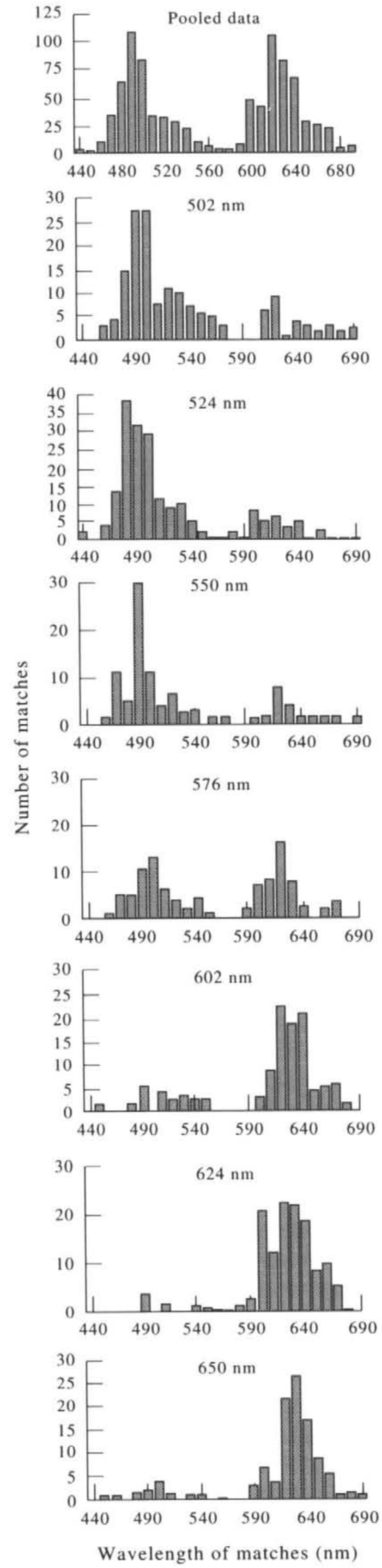

FIGURE 1. Krauskopf's perceived hue data are replotted here. Along the horizontal axis is plotted the wavelength of each suprathreshold matching stimulus (in nm) and along the vertical axis is plotted the number of trials for which that perceptual match occurred. The top panel shows the distribution of perceptual matches for all of the seven different test wavelengths pooled together. The other panels show the distributions of perceptual matches for each individual test wavelength, from 502 to 650 nm.

account for our data, although many of its predictions are similar to those described below for the noisy channels model.

Assumptions of generic multiple spatial-frequency channels model

The model is based on a generic multiple spatial-frequency channels model (Graham, 1989; Olzak & Thomas, 1986; Wilson *et al.*, 1983). The following assumptions hold true for any given location in the visual field:

1. There is a set of discrete, multiple spatial-frequency channels (bandpass filters) that operate in parallel. Each channel is maximally sensitive to a different spatial frequency, and responds to only a limited range of spatial frequencies,* although there is partial overlap in the sensitivities of neighboring channels.
2. On each trial the observer monitors all of the relevant channels and only those channels. That is, the observer attends *only* to those n channels which are most sensitive to the test stimuli used in the block of trials.
3. The output of each filter passes through a non-linear contrast transducer function (CTF). The contrast transducer function may be positively accelerated at lower contrasts, but is negatively accelerated at higher contrasts.
4. The output of each channel is perturbed by random noise which may cause trial-to-trial variability in the responses of each channel. The noise density functions are assumed to be identical for all of the channels: Here we assume that each channel's noise density function has a Gaussian distribution with a mean of zero ($\mu_n = 0$) and a standard deviation of one ($\sigma_n = 1$), the standard signal detection theory assumptions (Green & Swets, 1988; Macmillan & Creelman, 1991). Moreover, the channel outputs are probabilistically independent of each other.
5. The response of each channel on each trial is a single number, R_{it}, which corresponds to the response of the ith channel on trial t to a particular stimulus. In this noisy channels model we assume that the response criterion is set low enough that noise in a channel sometimes may be mistaken for a stimulus.
6. The output of each channel is perceptually labeled for spatial frequency, f_i. There is a monotonic relation between the optimal physical spatial frequencies for those channels and the perceptual labels attached to the respective channels.
7. The outputs of the different channels are combined according to some decision rule. This combination rule affects the perceived spatial frequency of a given spatial pattern. We will consider two combination rules here, a maximum output (or winner-take-all) rule and a weighted average rule. We assume that for near-threshold stimuli the subject uses either a *maximum output* or a *weighted average* combination rule, but uses the *same* rule for all blocks of near-threshold trials. For moderate-contrast stimuli, however, more than one channel responds vigorously and the subject uses a weighted average combination rule.

(a) *Maximum output* (*winner-take-all*) *rule*. The maximum output combination rule is given below:

$$I_t = f_{\mathrm{Max}(R_{it})}, \tag{1a}$$

where I_t is the perceived spatial frequency index on a given trial (t), $\mathrm{Max}(R_{it})$ is the response of the channel with the maximum output (of the n monitored channels), and $f_{\mathrm{Max}(R_{it})}$ is the perceptual label of the channel which produced the maximum response on that trial.

(b) *Weighted average rule*. An example of a weighted average combination rule (e.g., Davis, Kramer & Yager, 1986; Gelb & Wilson, 1983; Georgeson, 1980; Yager & Kramer, 1991) is shown below:

$$I_t = \sum_{i=1}^{n} (f_i R_{it}) \Big/ \sum R_{it}, \tag{1b}$$

where I_t is the perceived spatial frequency index on a given trial, f_i is the perceptual label for the ith channel, R_{it} is the ith channel's response on that trial to the stimulus or blank pattern, and there are n different channels in the set of monitored channels.

Processing of spatial patterns

Below we briefly consider the predictions of the model about the appearance of spatial patterns. In making these predictions we will consider how zero-contrast, near-threshold, and moderate-contrast spatial patterns are processed according to the model. Sometimes the predictions of the model will be modified because different assumptions hold (e.g., the maximum output versus weighted average combination rule).

For ease of explanation in describing how the spatial patterns are processed, consider the following: Suppose one tested over a range of spatial frequencies in a region where only two channels operate. Moreover, suppose each channel is maximally sensitive to a different spatial frequency and that these two channels partially overlap in their sensitivities to spatial frequency, as shown in the top panel of Fig. 2. Usually one channel would be more sensitive to a particular stimulus, of a given spatial frequency. This is shown in Fig. 2 by the stimulus labeled X, where the channel labeled "lower" is much more sensitive than is the channel labeled "higher." In Fig. 2b the channels' responses to stimulus X are shown by

*Although these channels also are selectively sensitive to other stimulus properties (e.g., orientation) and may even be perceptually labeled for at least some of these other properties, in these studies we emphasize the spatial frequency characteristics of the channels.

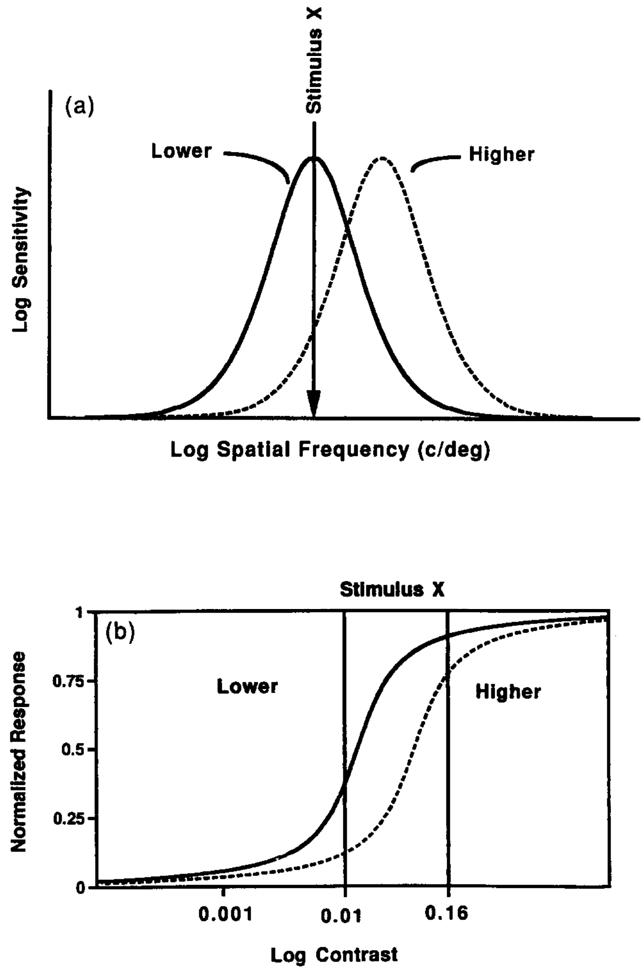

FIGURE 2. (a) The spatial-frequency sensitivity of two contiguous channels is shown in this figure, where log spatial frequency is shown on the horizontal axis and log sensitivity is shown on the vertical axis. The channel labeled "lower" has a peak sensitivity to a lower spatial than does the channel labeled "higher." The lower spatial-frequency channel is much more sensitive to the test stimulus labeled *X* than is the higher spatial-frequency channel. (b) The responses of two hypothetical contrast transducer functions (CTFs) to Stimulus *X* are shown in the bottom panel. The log contrast of the stimulus is shown on the horizontal axis and the normalized response of each CTF is shown on the vertical axis. The CTF labeled "lower" corresponds to the output of the lower spatial-frequency channel in the top panel and the CTF labeled "higher" corresponds to that of the higher spatial-frequency channel. The "lower" CTF is more sensitive to Stimulus *X* than is the CTF labeled "higher." So, at a near-threshold contrast of 0.01, the output of the "lower" CTF is about 0.50, but the output of the "higher" CTF is negligible. At a contrast of 0.16, however, both CTFs are responding vigorously.

two hypothetical contrast transducer functions, one labeled "lower" and the other "higher." Notice that at a near-threshold contrast of 0.01, only the lower spatial-frequency channel has a noticeable response to the stimulus. At a suprathreshold contrast of 0.16, however, both channels would respond vigorously to stimulus *X*. We will refer to this schematic again, when we compare how the near-threshold and moderate-contrast spatial patterns are processed according to the model.

Zero-contrast stimuli (blank stimuli). The results of several detection experiments in spatial vision (Davis & Graham, 1981; Thomas, Gille & Barker, 1982; Yager *et al.*, 1984) suggest that spatial frequency channels are noisy, and that noise within a channel can be mistaken for the response to a stimulus, resulting in false alarms. That is, the response criterion for the noise model is set low enough that sometimes noise is mistaken for a stimulus. We also assume here that the subject never guesses, but that all false alarms result from random noise perturbations in the channels. Hence, the lower the response criterion (or the noisier the channels), the larger the false alarm rate. Whenever a subject produces a false alarm on a blank trial, he or she must also produce a perceptual match for that trial. The histogram of the perceptual matches may allow us to determine which of the two combination rules is used. A histogram with a uniform distribution would support a noise model with a maximum-output rule. However, a normal distribution of perceptual matches on false alarm trials would support a noise model with a weighted average decision rule.

Near-threshold contrast stimuli. The model predicts that as the spatial frequency of the near-threshold test stimulus is gradually changed, the average perceptual match also will change relatively gradually and smoothly (see Fig. 3). The noise model with the weighted average combination rule predicts the smoother perceptual match function.

If a weighted average combination rule is used, the perceptual match histogram for individual test stimuli instead should show a unimodal peak that gradually changes as a function of the spatial frequency of the test stimulus. But, if a maximum output rule is used, the perceptual match histograms for the individual test stimuli may show a multimodal distribution, analogous to those Krauskopf reported for the perceived hues of flashed lights (see Fig. 1). In the latter case, one peak would correspond to the perceptual label of the most sensitive channel and another peak to the perceptual

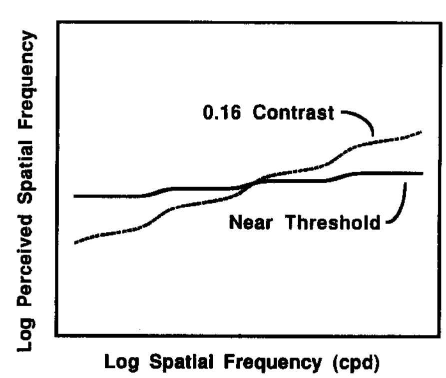

FIGURE 3. This simple schematic shows predicted results of the noise model. The physical spatial frequency of the test patterns is plotted along the horizontal axis (in log units) and the spatial frequency of the *average* perceptual match is plotted along the vertical axis (also in log units). The solid curve shows the function for the perceptual matches to the near-threshold test stimuli and the dashed curve shows the function for the matches to the 0.16 contrast test stimuli. Notice that the function for the near-threshold stimuli has a shallower slope than the function for the 0.16 contrast stimuli, but both functions are relatively smooth.

label of a neighboring channel that also is very sensitive to the stimulus. (However, the presence of a high false alarm rate or of broadly-tuned, overlapping spatial-frequency channels may obscure the multimodal peaks in the distribution. Yet, the underlying spatial-frequency channels are more narrowly tuned than are the mechanisms used in Krauskopf's perceived hue studies.)

Whether a weighted average or a maximum output rule is used, noise in the channels can affect the appearance of near-threshold stimuli. On a proportion of the near-threshold hits $(1-K)$, the output will be dominated by noise in at least one of the monitored channels. (The value $(1-K)$ is proportional to the false alarm rate on blank trials.) On the remaining proportion of the hits (K), the output will be dominated by one of the channels most sensitive to the stimulus. Moreover, the value s is the probability that the presence of the near-threshold stimulus is reported and the response is dominated by a channel sensitive to the stimulus (i.e., $s = K \cdot HR$, where HR is the hit rate). The average perceived spatial frequency index, I, is a weighted average of (1) the average perceived spatial frequency on trials which a channel or channels most sensitive to the stimulus dominate and (2) the average perceived spatial frequency on trials which noise dominates:

$$I = K \cdot f_S + (1-K) \cdot f_N = \frac{s \cdot f_S + (HR - s) \cdot f_N}{HR}, \quad (2)$$

where f_S is the average perceived spatial frequency when the signal from the stimulus dominates and f_N is the average perceived spatial frequency when noise dominates. The value of f_S is a weighted average that includes the perceptual labels of the channel (or channels) most sensitive to the stimulus.* The value of f_N can be estimated from the average perceptual match for false alarms produced on blank trials. Notice that if a lenient response criterion is used or if the channels are very noisy (relative to the responses of the most sensitive channels), the value of $(1-K)$ will be large. If $(1-K)$ is large, then the average perceived spatial frequency index will be pulled toward the weighted average of the noise and the range of perceived spatial frequencies will decrease. This will cause the slope of the near-threshold function to decrease (see Fig. 3).

Moderate-contrast stimuli. The model predicts that as the spatial-frequency of the moderate-contrast stimulus is changed, the average perceptual match also will change very smoothly and gradually (see Fig. 3). Moreover, the perceptual match histograms for the individual, moderate-contrast test stimuli will each show a unimodal peak that *gradually* changes as a function of the test pattern's physical spatial frequency. At these suprathreshold contrasts a weighted average combination rule is used and the response to the stimulus (i.e., the signal) is so large that it swamps any effects of random noise perturbations (see the bottom panel of Fig. 2).

Comparison of near-threshold and moderate-contrast perceptual match functions. Although all model versions predict the same slope for the moderate-contrast perceptual match function, they do not necessarily predict the same slope for the near-threshold perceptual match function. In fact, sometimes a steeper slope will be predicted for the near-threshold function and sometimes a shallower slope will be predicted. Some reasons are discussed below.

A multiple channels model with a false alarm rate of zero and with a maximum-output combination rule predicts that the near-threshold perceptual match function will have a steeper slope than the moderate-contrast function (*unlike* the near-threshold function shown in Fig. 3). The zero false alarm rate results either because the noise in the channels is extremely small compared with the response to the stimulus or because a very strict response criterion is used, so that noise is not mistaken for a stimulus. Thus, at near-threshold contrasts the perceived spatial frequency is pulled toward the perceptual label of the most responsive channel. (In Fig. 2 see the responses of the two contrast transducer functions to the near-threshold stimulus.) So, if the lowest or highest spatial-frequency channel dominates, then the perceived spatial frequency is pulled toward an extreme end of the spatial-frequency range. Although one channel is often more sensitive to a specific near-threshold stimulus, at a suprathreshold contrast more than one channel responds vigorously to that stimulus. (In Fig. 2 see the responses of the two contrast transducer functions to the moderate-contrast stimulus.) Thus, the system's overall response to a moderate-contrast stimulus would be a weighted average of these channels' responses. The perceived spatial frequency would be pulled toward the weighted average of these vigorously responding channels and away from an extreme end of the spatial-frequency range.

A multiple channels model with a relatively large false alarm rate or with a weighted-average combination rule predicts that the near-threshold perceptual match function will have a shallower slope (see Fig. 3). The effect of the noise is to pull the perceived spatial frequency of the near-threshold stimulus toward the middle of the spatial-frequency range (namely, toward the expected value of the labeled lines). Yet, at suprathreshold contrasts the response to the stimulus swamps any effects of noise. So, at a moderate, suprathreshold contrast the perceived spatial frequency would be pulled toward the weighed average of the vigorously responding channels and away from the midpoint of the spatial-frequency range.

Questions still to answer

To extend our understanding of how the human visual system encodes the appearance of near-threshold spatial patterns, compared with zero-contrast and

*If a weighted average rule is used on *each* trial, then f_S also includes perceptual labels of the noisy channels. If a maximum output rule is used on each trial, however, f_S only includes the perceptual labels of the channels sensitive to the stimulus.

moderate-contrast patterns, there are several questions to answer:

(1) What is the average perceived spatial frequency reported for false alarms produced on blank trials? Does it lie near the expected value of the perceived test spatial frequencies?
(2) What is the shape of the perceptual match histogram for false alarms produced on blank trials? Does the histogram for the false alarm matches have a uniform distribution (indicating a maximum-output rule)? Or, does it have a normal distribution (indicating a weighted average rule)?
(3) On near-threshold trials, what is the shape of the perceptual match histogram for pooled test stimuli? For each individual test stimulus? Is each histogram distribution multimodal (with consistent peaks and valleys) similar to those for Krauskopf's color vision data shown in Fig. 1? Or, is each distribution unimodal? If the distribution is unimodal, does the peak of each consecutive histogram change gradually as a function of the test spatial frequency?
(4) Is the near-threshold perceptual match function relatively smooth, compared with the moderate-contrast function (see Fig. 3)?
(5) Is the slope of the near-threshold perceptual match function shallower than the slope of the moderate-contrast function, as shown in Fig. 3?

METHODS

Apparatus and stimuli

Apparatus. Stimulus patterns were presented on two Tektronix 604 display oscilloscopes, with one scope positioned vertically above the other. The peripheral patterns were produced by an Apple II+ microcomputer with an 8-bit D/A board; an assembly-language program read stimulus tables stored in memory and controlled the outputs from the computer to the D/A board. A Tektronix waveform generator produced the high-contrast foveal patterns. The spatial frequency of the foveal pattern was determined by the Tektronix's voltage output, which was controlled by a potentiometer. An 8-bit A/D board in the computer monitored this voltage output. Both scopes had P31 phosphors that produce a desaturated green hue and were matched in mean luminance, 9 cd/m^2. An illuminated surround of approximately the same desaturated green hue and mean luminance framed the two visual displays; there were two rectangular apertures in the surround, 1.5 deg vertical by 4.0 deg horizontal, which were set at a distance of 8 deg apart, center to center. A numeric key pad was used to present stimuli and record responses.

Stimuli. The foveally viewed comparison stimuli were high-contrast patches of gratings. The peripherally viewed test stimuli were patches of gratings presented at 8 deg in the superior visual field. For channels located at 8 deg in the superior visual field, masking data show that the two highest spatial-frequency channels have a peak spatial frequency of approximately 2.9 and 5.7 c/deg with a half-amplitude bandwidth of 1.25 octave (Swanson & Wilson, 1985). Thus, the chosen range of peripheral test spatial frequencies, 1.5 to 4.0 c/deg, should include only two, or possibly three, narrow-band spatial-frequency channels. The peripherally viewed sinewave gratings had spatial frequencies of 1.5, 1.73, 1.99, 2.28, 2.63, 3.02, 3.48 or 4.0 c/deg.

The peripheral test stimuli were either set to a contrast of 0.16 or were set at detection threshold. (In this study, detection threshold is defined as the contrast which produces a correct response on 82% of the trials in a 2IFC detection paradigm.) Contrast for all stimuli was defined as follows:

$$\text{Contrast} = \frac{(L_{\max} - L_{\text{mean}})}{L_{\text{mean}}}, \qquad (3)$$

where $L_{\max}$ and L_{mean} are the maximum and mean luminances of the visual pattern, respectively. All test contrasts used were within the linear range of the display phosphors, as determined by calibration with a Pritchard photometer.

Procedures

Perceived spatial frequency matches. To match the perceived spatial frequency of the peripherally viewed sinewave grating, the periodicity of the foveal grating was set using a method of adjustment procedure. We were not producing a complete metameric match, but rather a perceptual match of perceived periodicity.

There were two experimental conditions. In one condition the peripheral test stimuli had a contrast of 0.16; in the other condition the peripheral test stimuli were set at contrast detection threshold, as determined from preliminary testing described below. There were usually five sessions per subject for each experimental condition. However, there were nine sessions for subjects RG and SN in the near-threshold condition. Within a given session there were 10 trials at each test stimulus for a total of 80 trials; moreover, in the near-threshold condition there were 80 blank trials randomly intermixed with the 80 stimulus trials. For most subjects there was a total of 50 trials per test stimulus in each condition; for subjects RG and SN there was a total of 90 trials per test stimulus in the near-threshold condition. Before each session the subject adapted for 2 min to uniform, blank displays set at the mean luminance setting.

To initiate a trial, after a subject began fixating on the fixation targets of the lower screen, she pressed "0" on a numeric keypad. A trial consisted of a 500 msec test stimulus or a blank presented on the top display, marked by a 500 msec tone, followed by a grating presented continuously on the bottom display until the subject made a response. If the subject did not see the peripheral test stimulus, she pressed "2" on the numeric keypad. If the subject did report seeing the peripheral test stimulus, she then used a potentiometer to adjust the physical periodicity of the foveal pattern until it matched the perceived periodicity of the peripheral stimulus; when a perceptual match was obtained, she pressed "1" on the numeric keypad to record the response. On some blank trials, a subject might report that a peripheral test stimulus was presented. In this case, the subject also would produce a perceptual match for the blank, or false alarm, trial. No feedback was provided on any trial.

In making the response, the subject was instructed to use only one of the following criteria throughout all of the sessions: (1) the distance between two neighboring dark bars; or (2) the width of a bright-dark pair of bars. (The subject could choose which of these two criteria to use. A control study showed that it made no difference which of the two criteria the subject used.)

In both the perceptual match condition and the preliminary testing, all stimuli were viewed binocularly, with the subject's head held in position by a chin rest and a forehead restraint. The displays were viewed from a distance of 155 cm. The subject's eye level was centered on the foveal stimulus.

Preliminary testing—contrast sensitivity function. To equate detectability of the peripherally viewed test stimuli, contrast detection thresholds were determined for each test pattern prior to conducting the matching experiment. The test stimuli were presented in four randomized blocks of staircases so that the contrast detection threshold for each test stimulus was based on the average of four threshold estimates. A PEST staircase procedure, with temporal two-interval forced-choice trials, was used to determine each detection threshold estimate. (On average, these detection thresholds correspond to contrasts that produce correct responses on 82% of the trials, resulting in a d' of 1.29. See Davis *et al.* (1986) and Rendleman, Rose and Teller (1970) for details of the PEST procedure used here.) Before each PEST staircase the subject light adapted for 2 min to a peripheral, uniform, blank field at the mean luminance setting.

The subject fixated a foveal target, then initiated a trial by pressing "0" on the numeric keypad. On each trial the peripheral stimulus randomly appeared in the first or second temporal interval. The interval duration and the pause between the two intervals of each trial were 500 msec, with abrupt onset and offset of the stimulus; an auditory tone marked the duration of each interval. The subject was told to press "1" if the stimulus appeared in the first interval and to press "2" if it appeared in the second interval. Two short beeps were provided as auditory feedback for each incorrect response.

Subjects

Six female subjects participated in both conditions of this experiment and in the preliminary testing. Five of these subjects were naive about the purpose and results of this experiment; the sixth subject was an author. Three of the subjects were corrected myopes and the other three were emmetropes. All subjects had a best-corrected Snellen acuity of 20/20 for near and for far distances. None of the subjects had any other clinically-significant visual deficits.

RESULTS

The perceived spatial-frequency matches yielded several notable results. First, on blank trials subjects sometimes produced a false alarm and also produced perceptual matches for those false alarms. Usually, the average match setting for the false alarms lies almost midway between the extreme ends of the perceived test spatial frequencies. Second, most histograms of the false alarm match settings are normally distributed around the mean. Third, most histograms of the near-threshold perceptual match settings show *no* evidence of a consistent multimodal distribution, unlike Krauskopfs perceived hue matches shown in Fig. 1. Fourth, the perceptual match functions are relatively smooth, both for the near-threshold test stimuli and for the moderate-contrast test stimuli. Fifth, at near-threshold contrasts the range of perceived spatial frequencies is smaller than it is at a higher, moderate contrast. Finally, according to Signal Detection Theory calculations, the detectability of the near-threshold test stimuli used in the matching experiment is equivalent to those in the preliminary study. We will discuss each of these results in more detail below.

Perceptual match histograms

The average perceptual match for false alarms ranges from 2.25 to 3.81 c/deg, as shown in Table 1. The average perceptual match for the false alarm trials also is shown for each subject by the dotted lines in Fig. 4. For five subjects the average false alarm match lies near the cross-over point of the near-threshold and moderate-contrast perceptual match functions, as shown in Fig. 4. The distributions of the false alarm match settings are shown for each subject in Fig. 5. Notice that most histograms of the false alarm match settings would be better fit by a normal distribution than by a uniform distribution. (Subject RL has such a low false alarm rate, 0.03, that it is difficult to estimate the distribution of her false alarm matches.)

The perceptual match histograms for near-threshold test stimuli show a unimodal distribution for five of the six subjects, unlike the perceptual match histograms shown in Fig. 1 for Krauskopf's color vision data. Moreover, the peak of each individual histogram gradually changes as a function of the test spatial frequency. The perceptual match histograms for near-threshold test stimuli are shown in Fig. 6 for two subjects who have very low false alarm rates (RG and RL). The top row shows the histograms of the perceptual match settings pooled across all of the near-threshold test stimuli. The lower rows show the perceptual match histograms for each individual, near-threshold test stimulus. The perceptual match histograms for near-threshold test stimuli are shown in the left set of panels of Fig. 7 for a subject who has a very high false alarm rate (RY). The data of subjects RG and RY

TABLE 1. Perceived spatial frequency matching condition

Subject	Slope of near-threshold match function	Slope of moderate contrast match function	Ratio of slopes	Average match spatial frequency for false alarms	*FAR*	*HR*	d'	Probability of detection (corrected for guessing)
MB	0.493	1.526	0.323	2.79 (2.88)	0.413	0.733	0.84	0.546
RY	0.420	1.130	0.372	3.81 (3.89)	0.403	0.844	1.26	0.739
SN	0.564	1.056	0.534	2.25 (2.14)	0.178	0.608	1.20	0.523
BD	0.766	1.084	0.707	3.34 (3.63)	0.118	0.543	1.29	0.482
RG	0.529	0.742	0.713	2.33 (2.45)	0.067	0.667	1.93	0.643
RL	0.745	0.915	0.814	3.01 (3.27)	0.03	0.422	1.68	0.404
Mean (median)	0.586 (0.547)	1.076 (1.07)	0.577 (0.621)	2.92 (3.08)	0.202 (0.148)	0.636 (0.638)	1.37 (1.275)	0.556 (0.534)

are typical for five of our subjects. There are no multimodal distributions with consistent peaks and valleys in the perceptual match histograms for the individual test stimuli. Instead, the perceptual match histograms are unimodal and the peak of the individual histograms gradually changes as a function of the test spatial frequency. RL's data are atypical, however, and are shown in the right set of panels in Fig. 6: RL's individual perceptual match histograms are multimodal and do show consistent peaks (e.g., at 0.17, 0.37 and 0.57 c/deg) and consistent valleys (e.g., at 0.27 c/deg) across the set of individual test stimuli. We will discuss these results later.

The perceptual match histograms for moderate-contrast test stimuli show a unimodal distribution, both for the individual test stimuli and for the data pooled across test stimuli. Moreover, the peak of each individual histogram gradually changes as a function of the test spatial frequency. The perceptual match histograms for moderate-contrast test stimuli are shown in the right set of panels in Fig. 7 for subject RY. Her results for moderate-contrast test stimuli are typical of *all* our subjects. The top, right panel shows the frequency histogram of the perceptual match settings pooled across all of the test stimuli for the 0.16 contrast stimuli. The lower right panels show the results for each individual peripheral test stimulus at 0.16 contrast. In none of these histograms is a multimodal distribution of perceptual matches convincingly shown. The histograms for the other five subjects show a similar pattern of results for the moderate contrast test stimuli.

Perceptual match functions

The perceptual match functions shown in Fig. 4 are relatively smooth, both for near-threshold test stimuli and for moderate-contrast test stimuli. This can be determined by visually inspecting the functions in Fig. 4. The coefficient of determination (r^2) was calculated for a straight line fitted through each set of data. For each of the near-threshold functions, the coefficient of determination lies between 0.89 and 0.98. For each of the moderate-contrast functions, the coefficient lies between 0.98 and 1.00. Thus, each set of data can be well fit by a linear function.

For near-threshold test stimuli the range of perceived spatial frequencies is smaller than it is for the 0.16 contrast test stimuli. This result is true for each of our six subjects. Across all subjects, the near-threshold function has a significantly shallower slope than does the moderate-contrast function [$t(5) = 3.64$, $P < 0.01$; see Fig. 4]. The slopes of the near-threshold and moderate-contrast functions are shown for each subject in Table 1. [Notice that the slope of the moderate-contrast function usually is close to 1.0. That is, the range of perceptual matches for the moderate-contrast patterns is equivalent to the range of physical test spatial frequencies. Notice also that the perceptual match often has a higher apparent spatial frequency than the physical spatial frequency of the test stimulus, as previously reported (e.g., Davis, 1990; Davis, Yager & Jones, 1987).*] Table 1 shows the ratios of the slope of the near-threshold match function to the slope of the 0.16 contrast match function. This ratio is inversely related to the subject's false alarm rate. Subjects with a higher false alarm rate also have a smaller ratio and vice versa.

*We did not expect veridical matches, because both the foveal stimuli and the underlying foveal perceptual mechanisms have different characteristics from those for the periphery. For instance, a peripherally viewed pattern has a higher perceived spatial frequency than does that *same* pattern when viewed foveally, presumably because of inhomogeneities in the visual system (Davis *et al.*, 1987; Swanson & Wilson, 1985). That is, a peripheral set of channels is tuned to lower spatial frequencies and has lower sensitivity than does the foveal set of channels, although the perceptual labels for the two sets of channels may be similar (Davis, 1990). So, instead of trying to obtain veridical or complete metameric matches, we were trying to obtain matches of the test pattern's perceived periodicity. Consequently, we expected to find, and did find, a monotonic relation between the foveal perceptual matches and the peripheral test spatial frequencies. The monotonic relation was obtained both for the near-threshold and for the moderate-contrast test stimuli.

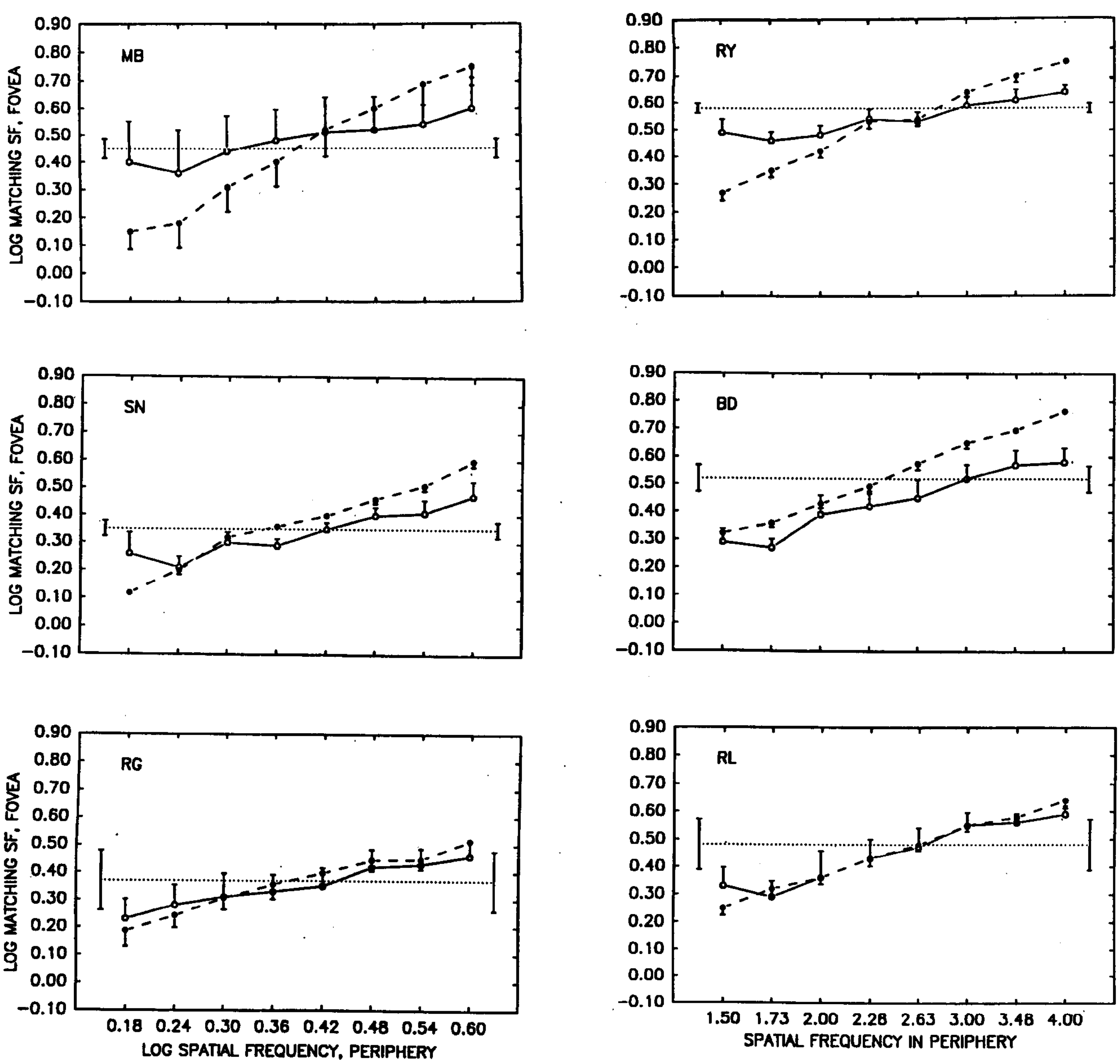

FIGURE 4. The *average* foveal match settings for each peripheral test stimulus is shown for each of the six subjects. The physical spatial frequency of the peripheral test pattern is plotted along the horizontal axis, in equal logarithmic steps, from 1.5 to 4.0 c/deg. The physical spatial frequency of the average foveal match setting is plotted along the vertical axis on a logarithmic scale. The open circles connected by a solid line show the average match settings for the near-threshold test stimuli and the solid circles connected by the dashed line show those for the 0.16 contrast test stimuli. The dotted lines indicate the mean match settings for false alarms produced on blank stimulus trials. The error bar for each data point shows 1 SEM, where ± 1.96 SEM approximates the 95% confidence interval. Data of the subjects with the highest false alarm rates are plotted in the top row and those with the lowest false alarm rates are plotted in the bottom row. Data of subjects with a lower spatial frequency match setting for false alarms are shown in the left column and those with a higher spatial frequency match setting are shown in the right column.

Detectability of near-threshold stimuli

Finally, Table 1 shows two different estimates of the subjects' sensitivity to the near-threshold test stimuli used in the matching procedure. One is the d' value, based on the standard Signal Detection Theory assumptions for yes–no trials [i.e., $d' = z(HR) - z(FAR)$]. The other is $p(c)$, the probability of detection corrected for guessing, based on the high-threshold theory's assumptions. In the preliminary study the contrast of each near-threshold test stimulus had been set by PEST staircase procedures so that the stimulus would be detected on 82% of the 2AFC trials. According to Signal Detection Theory, this corresponds to a d' value of 1.29. According to the high-threshold theory, this corresponds to a $p(c)$ value of 0.64. Remember, by chance alone the subject could guess correctly on 50% of the 2AFC trials. So, according to the high-threshold theory,

$$p(c) = (HR - 0.5)/(1 - 0.5) = (0.82 - 0.5)/0.5 = 0.64.$$

Thus, on the yes–no trials of the matching experiment, the detectability of the near-threshold stimuli should

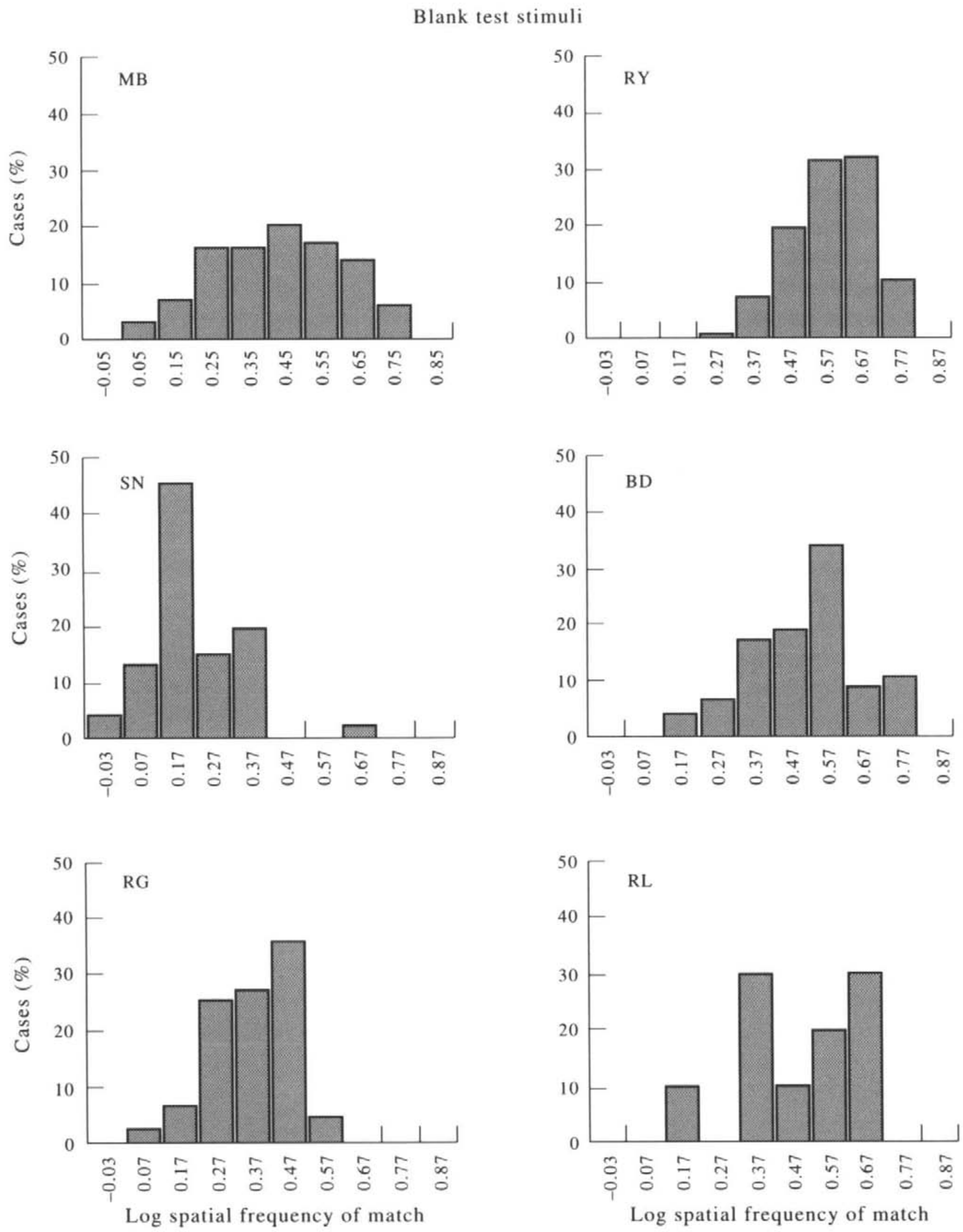

FIGURE 5. The histograms of the perceptual match settings for false alarms are plotted for each of our six subjects. Along the horizontal axis is plotted the log spatial frequency of the foveal match produced for these false alarm trials. Along the vertical axis is plotted the percent of cases for which that foveal match was produced. Data of subjects with the highest false alarm rates (RY and MB) are plotted in the top row and those with the lowest false alarm rates (RL and RG) are plotted in the bottom row. Five of these six histograms are better fit by a Gaussian probability distribution than by a uniform probability distribution.

correspond to a d' value of 1.29 or a $p(c)$ value of 0.64. Although the d' values shown in Table 1 do not significantly differ from the predicted value of 1.29 [i.e., $t(5) = 0.49$, $p > 0.20$], the $p(c)$ values do marginally differ from the predicted value of 0.64 [i.e., $t(5) = 1.73$, $0.05 < p < 0.10$].

DISCUSSION

Comparisons of theoretical predictions with the empirical results

In summary, all of our results are consistent with the predictions of a multiple spatial-frequency channels model that assumes noisy channels and either a weighted-average or a maximum-output combination rule. First, all subjects produced perceptual matches for false alarms on blank trials; the average false alarm match setting lies near the expected value of the perceptual labeled lines. Second, both the near-threshold and moderate-contrast perceptual match functions are relatively smooth (see Fig. 4). Third, the near-threshold perceptual match function has a smaller range of perceived frequencies than does the moderate-contrast match function. Fourth, for five of the six subjects there is no indication of a multimodal distribution in the perceptual match histograms for any of the

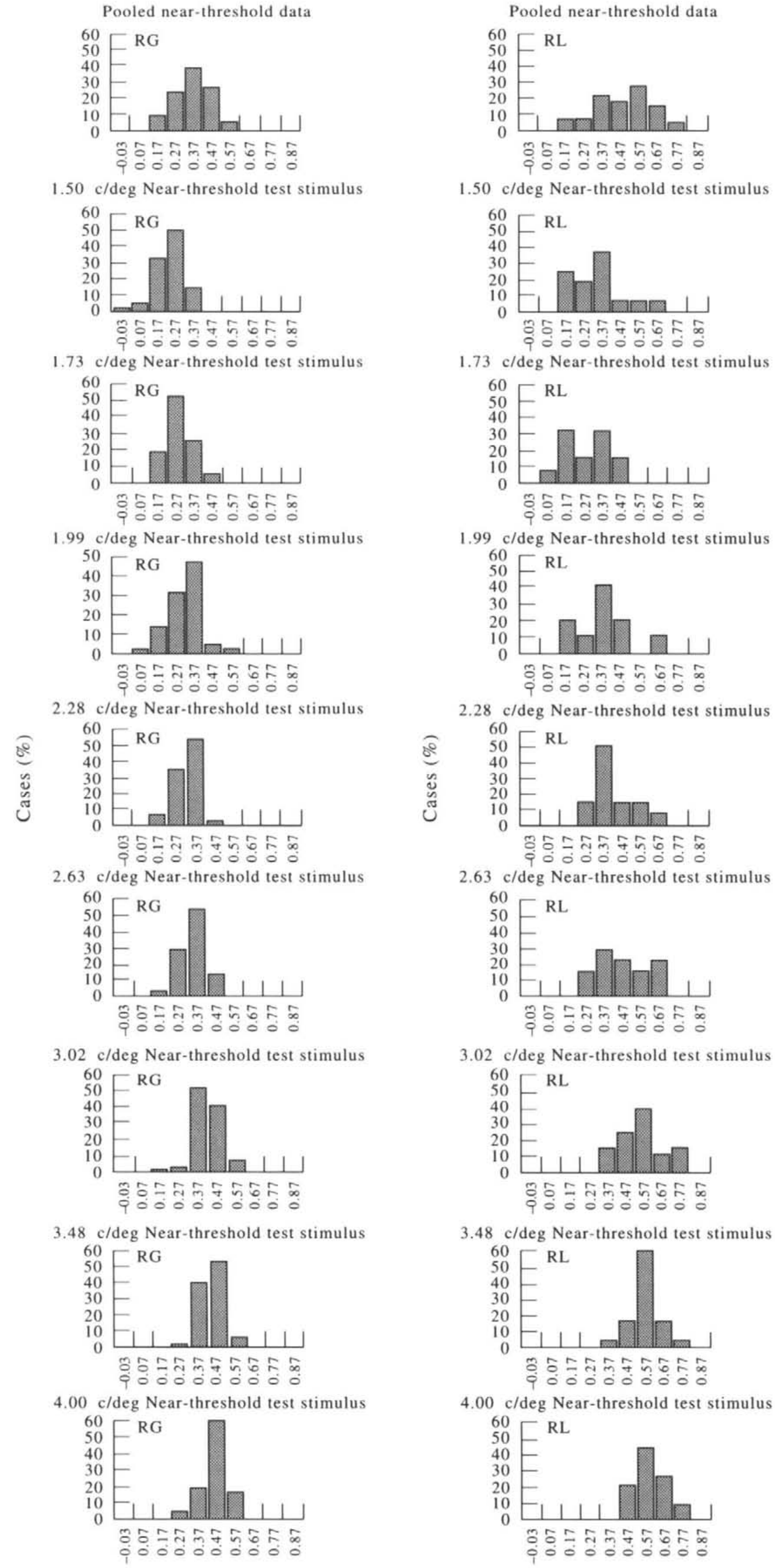

FIGURE 6. The histograms of perceptual matches for near-threshold spatial patterns are plotted for the two subjects with the lowest false alarm rates (RL and RG). These data are plotted in a form analogous to Krauskopf's hue matches shown in Fig. 1. Along the horizontal axis the spatial frequency of the match setting is shown. Along the vertical axis is plotted the percent of cases for each foveal match setting. The top panels show the histograms of the pooled data, where the perceptual matches for all eight, near-threshold stimuli have been combined. The other panels show the histograms of the perceptual matches for each individual, near-threshold stimulus, from 1.5 to 4.0 c/deg.

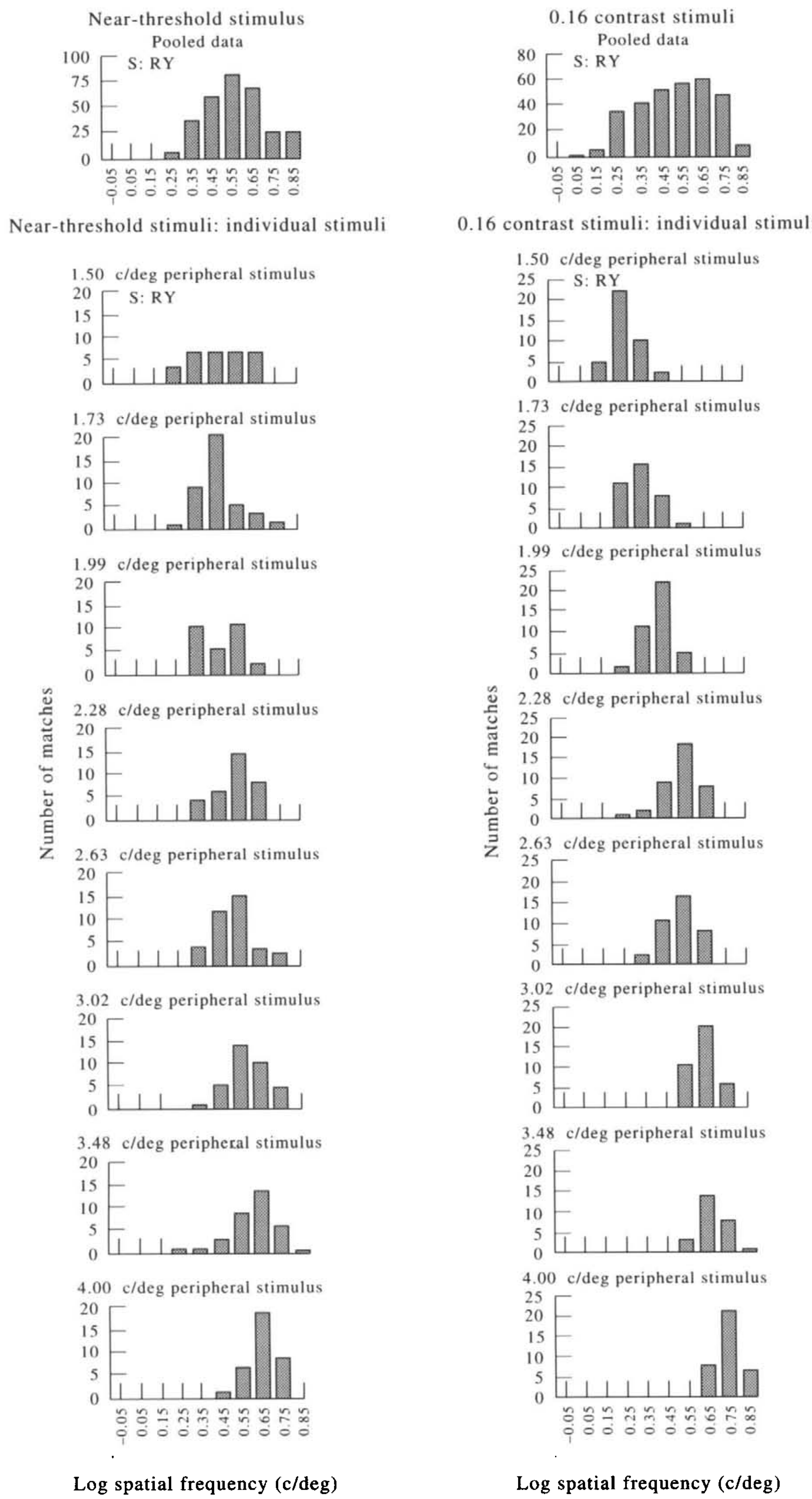

FIGURE 7. The histograms of the perceptual matches for spatial patterns are plotted for one subject with a very high false alarm rate, RY. These data are plotted in a form analogous to the perceptual match histograms shown in Fig. 1 for Krauskopf's color vision data. Along the horizontal axis is plotted the spatial frequency of each foveal match stimulus (on a logarithmic axis in c/deg) and along the vertical axis is plotted the number of trials for which that perceptual match occurred. The top panels show the distributions of perceptual matches for all eight test spatial frequencies pooled together; pooled data for the near-threshold test stimuli are shown on the left and those for the 0.16 contrast test stimuli are shown on the right. The other panels show the distributions of perceptual matches for each individual test spatial frequency, from 1.5 to 4.0 c/deg; again, distributions for the near-threshold test stimuli are shown on the left and those for the 0.16 contrast test stimuli are shown on the right.

near-threshold stimuli. Instead, each of their individual histograms has a unimodal distribution and the peak of each individual histogram changes gradually as a function of the test spatial frequency. Finally, according to SDT calculations of d', detectability of the near-threshold stimuli is equivalent on the yes–no trials of the matching study and the 2AFC trials of the preliminary study, as previously reported by other investigators (Green & Swets, 1988; Nachmias, 1981). It seems that noise perturbations within each channel can affect the overall response of the visual system and, thus, also affect the appearance of near-threshold and blank patterns. The predictions of the noisy channels model are consistent with all of our data and provide a parsimonious explanation. We will examine these conclusions in more detail below.

False alarms. The average perceptual match on false alarm trials lies near the middle of the range of perceived spatial frequencies, as predicted (see Fig. 4). Most histograms of the false alarm matches shown in Fig. 5 have an approximately normal distribution. These distributions indicate that most subjects used a weighted average rule to combine the noisy channels' outputs.

Near-threshold perceptual match histograms. Five of the six subjects have near-threshold perceptual match histograms that are unimodal; moreover, the peak of the individual histograms changes gradually as a function of the test spatial frequency. The predictions of the noisy channels model with a weighted average combination rule are consistent with the near-threshold histograms for these five subjects. The results of one subject (RL), however, are consistent with the predictions of the noisy channels model with a maximum output combination rule: her near-threshold histograms suggest multimodal distributions with consistent peaks and valleys, similar to those shown in Fig. 1 for Krauskopf's data.

The noisy channels model provides a parsimonious explanation for the data of all six subjects; for perceiving near-threshold stimuli, five of our subjects used a weighted combination rule and one subject (RL) used a maximum-output combination rule. In fact, this suggests a possible explanation why most of our near-threshold histograms look so different from Krauskopf's perceived hue histograms. Perhaps *all* of his subjects used a maximum-output combination rule. Another possible explanation for the discrepancy is that Krauskopf eliminated some of the data from the analysis. [Krauskopf reasoned that if a small, dim stimulus appeared to be yellow or white, it must be stimulating more than one type of cone. Because he wanted to stimulate only a single cone type, he eliminated data of these ambiguous stimuli from the data analyses. Other researchers (e.g., Cicerone & Nerger, 1989) also have used this approach when trying to isolate the operation of a single cone type.]

Perceptual match functions. Figure 4 shows each subject's average perceptual match for each near-threshold and moderate-contrast test stimulus.

First, the relatively smooth perceptual match functions shown in Fig. 4 for the near-threshold stimuli are consistent with the noisy channels model. The assumption about variable outputs of the channels and the assumption about a weighted average combination rule each predict that the near-threshold function should be relatively smooth.

Second, the range of perceived spatial frequencies at near-threshold contrasts is smaller than the range at moderate contrasts. These data agree with those of another study which used a different procedure (i.e., a PEST staircase procedure with 3AFC trials), different spatial patterns (D6 luminance patterns), and different subjects (Kirkland, Davis, Yager, Surdick & Hochstein, 1993). The shallower near-threshold slope is predicted because noise would pull the perceived spatial frequency of the near-threshold stimulus toward the expected value of the relevant labeled lines and away from an extreme end of the spatial-frequency range.

In Fig. 4 notice that the false alarm match setting usually lies near the crossover point of the near-threshold and moderate-contrast perceptual match functions. Also, the slope of the near-threshold function is shallower than that of the moderate contrast function. These two results suggest the perceived spatial frequency of a near-threshold stimulus could be a *combination* of the percept produced by the response to the stimulus and the percept produced by noise, whereas the perceived spatial frequency of the 0.16 contrast stimulus is a percept produced only by the response to the stimulus. This noise model interpretation of the near-threshold perceptual match function is given by an equation previously described in the Theory section:

$$I = K \cdot f_S + (1 - K) \cdot f_N = \frac{s \cdot f_S + (HR - s) \cdot f_N}{HR}, \quad (2)$$

where I is the average perceived spatial frequency for a specific near-threshold test stimulus, K is the proportion of the hit rate (HR) on which the percept (f_S) is produced by the response to the stimulus and $(1 - K)$ is the proportion of the hit rate on which the percept (f_N) is produced by the response to noise. Moreover, s is the probability that near-threshold stimulus is detected and the response is dominated by a channel sensitive to the stimulus. With noisier channels or a more lenient response criterion, a larger value of $(1 - K)$ will result and, consequently, the near-threshold perceptual match function will be shallower.

We cannot quantitatively test the predictions of this model for a few reasons. First, we do not have a good estimate of the average match produced by the response to the stimulus (f_S) on near-threshold trials. We do not know the actual perceptual labels of the spatial-frequency channels in the periphery. The match produced for the moderate-contrast test stimulus is not a good estimate of the value of f_S near threshold. At a moderate contrast several channels may respond vigorously to the stimulus, although only one channel may be very sensitive at a near-threshold contrast. (For example, see the responses to a near-threshold and moderate-contrast stimulus in Fig. 2b.) Second, if more than one channel is sensitive to the near-threshold test stimulus, we must estimate the relative sensitivities of those channels and modify the simplified equation shown above.

Another possible interpretation of these data is based on a high-threshold theory, whose assumptions and predictions are given below and compared with those of the noisy multiple channels model.

A high-threshold interpretation of the near-threshold perceptual match function

For the high-threshold model, we assume that the internal threshold criterion is set very high above the noise level (e.g., $+3\sigma$) so that random noise perturbations are *never* mistaken for a stimulus (Green & Swets, 1988). We also assume that near threshold the subject always uses a maximum-output combination rule.* That is, a stimulus is detected if and only if the maximum output of the monitored channels exceeds the high threshold criterion. If the subject detects the stimulus, he or she always reports that the stimulus is present. But, if the subject does not detect a stimulus, he or she sometimes may guess that a stimulus is present. When the subject guesses that a stimulus is present, a "perceptual" match is produced by guessing. The false rate on blank trials is the estimated probability that the subject guesses when a stimulus is not detected. Hence, for near-threshold patterns the probability of detection corrected for guessing† is

$$p = (HR - FAR)/(1 - FAR), \tag{4}$$

*Notice that if the response criterion is so strict that noise cannot be mistaken for a stimulus and if only one channel responds to a given stimulus on a given trial, the weighted average combination rule is equivalent to a maximum output or a winner-take-all rule. In the high-threshold model, the stimulus is detected whenever the output of the most responsive channel exceeds threshold (namely, a maximum output rule) for the reasons given here. The response of a given channel to a particular stimulus is given by the following equation (Graham, 1989; Quick, 1974):

$$R_i = [c \cdot S_i]^k,$$

where c is the contrast of the stimulus, S_i is the sensitivity of the channel to the particular stimulus (i.e., the reciprocal of the detection threshold contrast), and k is a constant set to infinity ($k = \infty$). If the stimulus contrast is less than the threshold contrast for a given channel, i, then the response of the channel, R_i, is zero. That is,

$$R_i = \lim_{k \to \infty} (c \cdot S_i)^k = 0, \quad \text{if } (c \cdot S_i) < 1.$$

The probability that the ith channel detects the stimulus is given by the following equation:

$$P_i = 1 - 2^{-R_i}.$$

So, if R_i is zero, then there is a probability of zero that the ith channel detects the stimulus [namely $P_i = 1 - (1/2)^0 = 1 - 1 = 0$]. If the stimulus contrast is greater than the detection threshold contrast of the ith channel, however, then the response of the channel, R_i, is the maximum (namely, infinity). That is,

$$R_i = \lim_{k \to \infty} (c \cdot S_i)^k = \infty, \quad \text{if } (c \cdot S_i) > 1,$$

and there is a probability of one that the ith channel detects the stimulus [namely, $P_i = 1 - (1/2)^\infty = 1 - 0 = 1$]. The probability that the stimulus is detected is given by the following equation:

$$P = 1 - \Pi(2^{-R_i}),$$

where the second term is the product of all the probabilities that each channel does *not* detect the stimulus. When the stimulus is detected by the most responsive channel, the value of the second term will be zero, and the probability of detection is one. So, for the high-threshold model, the combination rule is equivalent to a maximum output rule.

†The probability s in the noise model is analogous to p, the high-threshold probability of detection corrected for guessing. But, the probability s in the noise model should be larger than the probability p in a high-threshold model for reasons given here. For ease of comparisons in showing why s is greater than p, we will assume that a maximum output detection rule is used both in the noise model and in the high-threshold model. Also for ease of comparisons, we will assume that only one channel is very sensitive to the stimulus. In the high-threshold model, the false alarm rate (FAR) is the estimated guessing rate, both on blank trials and on near-threshold stimulus trials. This guessing rate is used to correct the probability of detection for guessing and determine the "true detection rate," p, for a near-threshold stimulus. That is, in the high-threshold model we assume the guessing rate does not change for blank or near-threshold stimuli. In the noise model we assume that the response of at least one of the monitored channels exceeds the response criterion on any trial that the subject reports a stimulus present and that the subject does not guess. If there are n monitored channels, on blank trials a false alarm sometimes occurs because noise in one of the monitored channels is mistaken for a stimulus. That is,

$$FAR = 1 - (1 - q)^n,$$

where FAR is the false alarm rate, q is the probability that noise in a given channel exceeds the response criterion, and n is the number of monitored channels. (Remember, we assume that each channel has the same noise density function and that each channel's output is independent of any other channel's output.) On near-threshold stimulus trials, a hit occurs because either the response of the channel most sensitive to the stimulus or noise in of one of the other $(n - 1)$ monitored channels exceeds the response criterion. That is

$$HR = 1 - [(1 - s)(1 - q)^{n-1}],$$

where HR is the hit rate, s is the probability that the response in the most sensitive channel exceeds the response criterion, q is the probability that noise in a given channel exceeds the response criterion, and n is the number of monitored channels. If we rearrange the terms to define s and p, we have the following equations and inequality:

$$s = \frac{\{(HR - FAR) + [q \cdot (1 - HR)]\}}{(1 - FAR)} \geqslant \frac{(HR - FAR)}{(1 - FAR)} = p.$$

Notice that if q is zero (i.e., the noise in any given monitored channel *never* exceeds the response criterion) or if the hit rate is one, then s is equal to p, the high-threshold probability of detection corrected for guessing. But, in the noise model, whenever q is zero, then the false alarm rate also will be zero and p will be equal to the hit rate.

where HR is the hit rate on near-threshold trials and FAR is the false alarm rate on blank trials (e.g., Green & Swets, 1988; Macmillan & Creelman, 1991).

A high-threshold interpretation of the near-threshold perceptual match function is that the perceived spatial frequency of a near-threshold stimulus is a combination of the percept produced by the response to the stimulus and the guessed matches produced on false alarm trials. For ease of explication, this high-threshold model interpretation of the near-threshold perceptual match function is given by a simplified equation:

$$I = \frac{p \cdot f_S + [(FAR)(1-p)] \cdot f_g}{HR} \quad (5)$$

where p is the probability of detection corrected for guessing, f_g is the average match produced by guesses when the stimulus is not detected, and FAR is the false alarm rate. A higher the false alarm rate will result in a shallower near-threshold perceptual match function, in agreement with our data.

This high-threshold interpretation of our data is unlikely, however, because the high-threshold model fails to predict other results. According to high-threshold model calculations, the detectability of the near-threshold test stimuli used in the matching experiment are *not* equivalent to those used in the preliminary study. Yet, because the preliminary 2AFC detection study was used to determine the near-threshold contrasts used in the yes–no matching procedure, the detectability of both sets of stimuli should be equivalent. In fact, calculations based on signal detection theory show that both sets of test stimuli are equally detectable. Thus, the noisy multiple channels model provides the more probable explanation of our data.

Comparison with theoretical interpretations for previous high-contrast results

Investigating the appearance of zero-contrast (blank), near-threshold, and moderate-contrast spatial patterns extends previously published research on perceived spatial frequency: In most published research only suprathreshold patterns were used to study the changes in perceived spatial frequency as a function of contrast (e.g., Davis *et al.*, 1986; Gelb & Wilson, 1983; Georgeson, 1980; Parker, 1980).

In those previous studies, one theoretical explanation of the suprathreshold shifts in perceived spatial frequency assumes that a nonlinear contrast transducer function (CTF) follows the output of each bandpass filter in a set of spatial frequency channels (see Fig. 2b). The nonlinear CTFs are less compressive at lower, suprathreshold contrasts than they are at higher contrasts. Thus, at moderate contrast levels, the response of the most sensitive channel is operating at a less compressive portion of its CTF, so that a change in contrast will produce a change in the output of that channel. Yet, at higher contrast levels the response of the most sensitive channel is saturated, so that even a *large* change in the contrast produces *no* change in the output of that channel. Meanwhile, less sensitive, neighboring channels also respond at the higher, suprathreshold contrast levels. Because these less sensitive channels are responding on less compressive portions of their respective CTFs, a large change in contrast will produce a noticeable change in the outputs of these neighboring channels. Consequently, at higher suprathreshold contrasts the perceived spatial frequency of the stimulus will be pulled toward the mean of the labeled lines and away from an extreme end of the spatial frequency range. Hence, the range of perceived spatial frequencies at higher suprathreshold contrasts is smaller than it is at a lower, moderate suprathreshold contrast. The reasons are explained in more detail elsewhere (Davis *et al.*, 1986; Gelb & Wilson, 1983; Kirkland *et al.*, 1993).

We can combine the above theoretical explanation for the high contrast patterns with those for the appearance of near-threshold patterns. For near-threshold patterns the noise model provides the appropriate predictions and explanations, as previously described. Combining the predictions for the high-contrast, moderate-contrast, and near-threshold spatial patterns results in the following set of predictions.

(1) The range of perceived spatial frequencies is larger at a moderate contrast than it is at either a lower, near-threshold or a higher, suprathreshold contrast.
(2) There may be a change in the direction of the perceived spatial frequency shifts as one increases the contrast of a given sinewave grating from a very low contrast to a very high contrast. For instance, a low spatial frequency pattern will have a lower perceived spatial frequency at a moderate contrast than it will at either a lower, near-threshold or a higher, suprathreshold contrast.

CONCLUSIONS

In conclusion, our results extend our understanding of how spatial-frequency channels encode the appearance of near-threshold sinewave gratings, compared with blank or suprathreshold spatial patterns. In our studies, we found that the noisy multiple channels model (with either a weighted average or maximum output combination rule) could account for all of our data. A high-threshold model with guessing is an alternative model, but it could not account for all of the data. Both the noise and high-threshold models predict the following results which are consistent with our data.

(1) A smooth perceptual match function for near-threshold stimuli and for moderate-contrast stimuli.
(2) The range of perceived spatial frequencies is smaller near threshold than at the moderate suprathreshold contrast of 0.16.
(3) The perceived spatial frequency of a near-threshold stimulus is a combination of the percept produced by the response to the stimulus and by

either the percept produced by noise or the matches produced by guesses.

However, the detectability of near-threshold stimuli on the yes–no trials of the matching procedure also were consistent with the predictions of the noise model (d' values), but not with the predictions of the high-threshold model (p, the probability of detection corrected for guessing).

Thus, the noisy multiple channels model is more consistent with our data and provides a more parsimonious explanation than the high-threshold model. Noise may affect the appearance of near-threshold visual patterns and the effect of the noise can be measured by the subject's response to zero-contrast (blank) stimuli.

REFERENCES

Cicerone, C. M. & Nerger, J. L. (1989). The relative numbers of long-wavelength-sensitive to middle-wavelength-sensitive cones in the human fovea centralis. *Vision Research, 29,* 115–128.

Davis, E. T. (1990). Modeling shifts in perceived spatial frequency between the fovea and the periphery. *Journal of the Optical Society of America, A, 7,* 286–296.

Davis, E. T. & Graham, N. (1981). Spatial frequency uncertainty effects in the detection of sinusoidal gratings. *Vision Research, 21,* 705–712.

Davis, E. T., Kramer, P. & Yager, D. (1986). Shifts in perceived spatial frequency of low-contrast stimuli: Data and theory. *Journal of the Optical Society of America, A, 3,* 1189–1202.

Davis, E. T., Yager, D. & Jones, B. J. (1987). Comparison of perceived spatial frequency between the fovea and the periphery. *Journal of the Optical Society of America, A, 4,* 1606–1611.

Davis, E. T., Yager, D., Richter, E., Woodward, M. & Kramer, P. (1984). Shifts in perceived spatial frequency of low contrast gratings as a function of contrast. *Investigative Ophthalmology and Visual Science (Suppl.), 25,* 314.

Gelb, D. J. & Wilson, H. R. (1983). Shifts in perceived size as a function of contrast and temporal modulation. *Vision Research, 23,* 71–82.

Georgeson, M. (1980). Spatial frequency analysis in early visual processing. *Philosophical Transactions of the Royal Society of London, B, 290,* 11–22.

Graham, N., Robson, J. G. & Nachmias, J. (1978). Grating summation in fovea and periphery. *Vision Research, 18,* 815–827.

Graham, N. V. S. (1989). *Visual pattern analyzers.* New York: Oxford.

Green, D. M. & Swets, J. A. (1988). *Signal detection theory and psychophysics.* Los Altos, Calif.: Peninsula.

Hirsch, J., Hylton, R. & Graham, N. (1982). Simultaneous recognition of two spatial-frequency components. *Vision Research, 22,* 365–375.

Kirlkand, B. A., Davis. E. T., Yager, D., Surdick, R. T. & Hochstein, A. (1993). Effects of contrast on perceived size of visual patterns: Theory, data, and implications. In *Proceedings of the Human Factors and Ergonomics Society 37th Annual Meeting,* 2 (pp. 1355–1359). Santa Monica, CA: Human Factors and Ergonomics Society.

Krauskopf, J. (1964). Color appearance of small stimuli and the spatial distribution of color receptors. *Science, 54,* 1171.

Krauskopf, J. (1978). On identifying detectors. In Armington, J., Krauskopf, J. & Wooten, B. (Eds), *Visual psychophysics and physiology.* New York: Academic Press.

Krauskopf, J. & Srebro, R. (1965). Spectral sensitivity of color mechanisms: Derivation from fluctuation of color appearance near threshold. *Science, 150,* 1477–1479.

Macmillan, N. A. & Creelman, C. D. (1991). *Detection theory: A user's guide.* New York: Cambridge University Press.

Nachmias, J. (1981). On the psychometric function for contrast detection. *Vision Research, 21,* 215–223.

Olzak, L. & Thomas, J. P. (1981). Gratings: Why frequency discrimination is sometimes better than detection. *Journal of the Optical Society of America, 71,* 67–70.

Olzak, L. A. & Thomas, J. P. (1986). Seeing spatial patterns. In Boff, K. R., Kaufman, L. & Thomas, J. P. (Eds), *Handbook of perception and human performance, Vol. 1, Sensory processes and perception.* New York: Wiley.

Parker, A. (1980). *Responses of the human visual system to the spatial structure of stimuli.* Ph.D., Cambridge University, Cambridge, England.

Quick (1974). A vector-magnitude model of contrast detection. *Kybernetik, 16,* 65–67.

Rendleman, P., Rose, R. M. & Teller, D. Y. (1970). Statistical properties of Pollack's PEST procedure. *Perception & Psychophysics, 9,* 208–212.

Richter, E. S. & Yager, D. (1984). Spatial-frequency difference thresholds for central and peripheral viewing. *Journal of the Optical Society of America, A, 1,* 1136–1139.

Swanson, W. H. & Wilson, H. R. (1985). Eccentricity dependence of contrast matching and oblique masking. *Vision Research, 25,* 1285–1295.

Thomas, J. P., Gille, J. & Barker, R. (1982). Simultaneous detection and identification: Theory and data. *Journal of the Optical Society of America, 72,* 1642–1651.

Watson, A. B. & Robson, J. G. (1981). Discrimination at threshold: Labeled detectors in human vision. *Vision Research, 21,* 1115–1121.

Wilson, H. R., McFarlane, D. K. & Phillips, G. C. (1983). Spatial tuning of orientation selective units estimated by oblique masking. *Vision Research, 23,* 873–882.

Yager, D. & Kramer, P. (1991). A model for perceived spatial frequency and spatial frequency discrimination. *Vision Research, 31,* 1067–1072.

Yager, D., Davis, E. T., Lee, R. & Neufeld, S. (1989). The appearance of medium-, low-, and zero-contrast spatial stimuli, and the labeled lines notion. *Investigative Ophthalmology and Visual Science (Suppl.), 30*(485).

Yager, D., Kramer, P., Shaw, M. & Graham, N. (1984). Detection and identification of spatial frequency: Models and data. *Vision Research, 24,* 1021–1035.

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